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Dynamic Modeling and Simulation of Transmotor Based Series-Parallel HEV Compared to Toyota Prius 2004 Planetary Gear

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ABSTRACT

In this paper, two different power dividers in different series-parallel topologies for hybrid electric vehicles have been compared. The first power divider which has been used in Toyota Prius 2004 is called Planetary Gear and is a mechanical device. The so called planetary gear is a set of gears which connects generator, electric motor and engine. The other power divider is called Transmotor and is an electromagnetic machine with both rotor and stator rotating. In this paper we developed a hybrid electric vehicle model based on United States Department of Energy Reports and used it as a benchmark for comparison.

KEYWORDS: Power Divider, Hybrid Electric Vehicles (HEV), Toyota Prius 2004, Transmotor, MATLAB Simulink

INTRODUCTION

Environmental pollution and energy crisis are the most concern of automotive industry in past four decade. In response, major automotive companies develop the technology of hybrid electric vehicle (HEV) to achieve better fuel economy and lower the emissions through the optimization of vehicle operation and engine operation [1], [2]. This performance is achieved by adding electrical devices such as electrical storage device and electrical motor to power and torque path of conventional automobiles with internal combustion engine (ICE) [3]. In order to design and test different strategies of HEVs, several computer modeling and simulation have to be used to examine and compare the performance of these vehicles. Based on their application, these models can be divided into two categories [4]:

Models for designing stage for high level operating strategies that include long-term analysis such as SIMPLEV from the DOE's Idaho National Laboratory[5], ADVISOR from the DOE's National Renewable Energy Laboratory [6] and PSAT from Argonne National Research Laboratories [7].

And the second category, which interactions between subsystems and their design are studied. In these models detailed subsystem models are used to address the dynamic behavior of HEV subsystem. V-Elph developed at Texas A&M University [8], PSIM-based model from Illinois Institute of Technology [9] are two dynamic simulators that use lower level of HEVs for studying detailed performance issues.

In this paper, authors tried to develop a dynamic model of a famous HEV that could validate with an acceptable and precise test result. For this purpose second generation of Toyota hybrid system (THS II) used in the 2004 Prius with information of U.S. Department of Energy (DOE) reports [10] was selected (Table I). This HEV model is one of famous HEV drive train and earns many awards for its designation such as Best Engineered Vehicle for 2004 selected by readers and editors of Automotive Engineering International (AEI) [11].

TABLE I
TOYOTA PRIUS 2004 COMPONENTS

Subassembly	Specifications	
	Description	**Value**
Vehicle	Weight	1360kg
Maximum vehicle speed	Electric mode	60 km/h
	Hybrid mode	160 km/h
Engine	Max power	57kw@5000rpm
Planetary gear	Ratio (ring, planet, sun)	2.6 (78/23/30)
Electrical motor	Max power	50 kW
	Maximum speed	6000 rpm
	Maximum torque	400 Nm (0–1200 rpm)
Electrical generator	Max power	30 kW
	Maximum speed	10000 rpm
	Maximum torque	160 Nm
battery	NiMh module number	28
	Nominal energy	1.3 kWh
	Nominal voltage	201.6 V

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Simulating new topologies and revisions is the cheapest and best way to prevent extra costs for vehicle industries. In this paper two power dividers has been simulated and compared. For this comparison, at first, a dynamic model for HEV has been introduced. The data used for modeling is elicited from United States Department of Energy (U.S. DOE) reports of experimental tests on Toyota Prius 2004[10], [12].

The model is designed so that it could be easily adjusted. With a special topology, the least differences have been made in other parts of the model so the results of comparison are more acceptable.

I. HYBRID ELECTRIC VEHICLE MODEL

For comparing two different power dividers at first we have to develop a benchmark model and then by implementing those power dividers into it, try to compare them. Toyota Prius 2004 has been selected as a bench mark and we have developed and evaluate it with real test data elicited from U. S. DOE's reports. Table I presents some of the vehicle's specifications. The model is a result of modifications in MATLAB Simulink model of HEV to satisfy real test results.

A. Simulink Model

The model presented here is based on MATLAB Simulink model for HEV with several changes in various subsystems and modifying model specifications (Fig. 1). The major changes are in energy management subsystem and ICE. Each subsystem will be individually described.

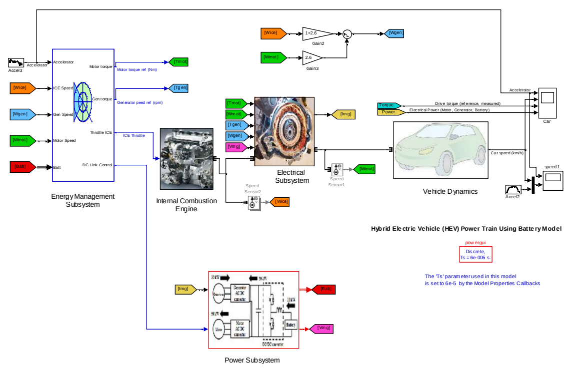

Fig.1: MATLAB Simulink model for Toyota Prius 2004

B. Energy Management

Energy management is mainly based on vehicle speed, subsystems speed (engine, motor and generator), input acceleration (Drive Cycle), and Battery's variables (voltage, current and State of Charge (SOC)).

This subsystem contains main controller for defining the amount of torque that each torque provider (ICE, Motor/Generators (MG)) should produce and is divided into three parts: battery management, hybrid management and ICE speed controller (Fig. 2).

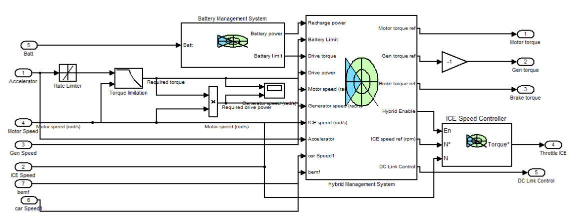

Fig. 2: Energy Management Subsystem

Battery management system receives battery's data values from energy storage subsystem to limit the range of SOC between 40% and 80% and specify amount of receiving or sending power for battery.

In Hybrid management subsystem (Fig. 3) the amount of required torque for engine, traction motor and generator will be defined. This procedure is done with the help of subsystem's rotating speed and demanded power and torque defined by the amount of acceleration and brake pedal from drive cycle. At first, state of hybridization is determined by demanded power, vehicle speed, and battery's SOC. In base model, moment of hybridization is not specified by vehicle speed, but according to DOE report, any increase in speed more than 24 km/h activates ICE [13], [14], therefore speed condition is added to model. Another correction in base model is in brake time, when the brake power exceeds the power power capacity limit of battery. In the base model, there is no mechanical brake simulator, so when battery can't absorb absorb regenerated energy the vehicle simply can't respond to the brake signal.

In presented model, additional power -which battery can't absorb- well be sent to a mechanical brake instead of motor and battery pack. In addition, A DC link voltage controller has been added to original model that provides ability to control dc link voltage in different vehicle cycling modes, and has not been considered in base model.

According to its current speed and characteristic, ICE speed controller, through its efficiency map produces reference torque for ICE. Note that the efficiency map in base model doesn't match with real map and this conflict has been removed in presented model.

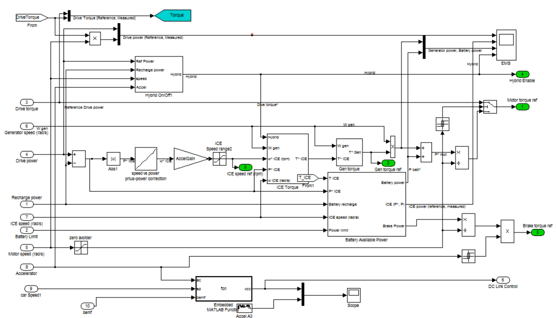

Fig. 3: Hybrid Management Subsystem

C. Electrical Subsystem

This subsystem contains motor, generator and planetary gear (Fig. 4). Motor has field weakening controller and its characteristic is similar to torque-speed map provided by DOE report [12].

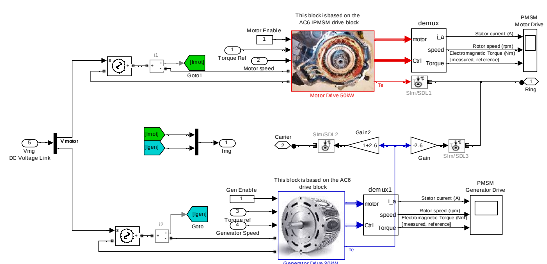

Fig. 4: Electrical subsystem containing torque relationships model for planetary gear

D. Power Subsystem

In this model, as depicted in Fig. 5, battery and DC-DC converter are placed in one block so that control strategy or its whole system could be changed and replaced with new systems. An additional ability to control DC-DC link voltage has been added to optimize switching losses, since it exists in real Prius 2004 model. With this ability in the future, various DC voltage link strategies could be investigated. So, here in this block, the difference between presented and base model is providing an additional ability to control DC Voltage link and also packing the whole blocks up together so that new strategies could be tested more convenient.

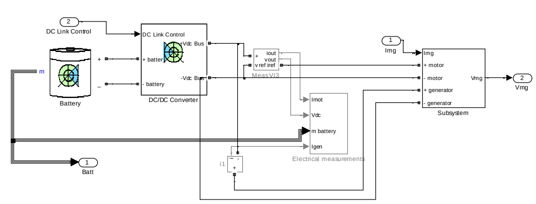

Fig. 5: Energy storage subsystem including DC-DC converter

E. ICE

For designing ICE in presented model, Toyota Prius 2004's characteristic has been used. Torque-speed characteristic of the ICE is a lookup table based on [12]. In energy management for controlling the ICE we need speed-power lookup table to estimate the amount of power needed to drive the vehicle so by modifying this table a speed-power lookup table has been produced. The lookup table is extracted from Fig. 6[15]. Maximum torque limitation of ICE has been extracted but the goal is to use ICE at its maximum efficiency. In Fig. 6 the highest line indicates the maximum torque limitation and the line under it shows the most efficient working area.

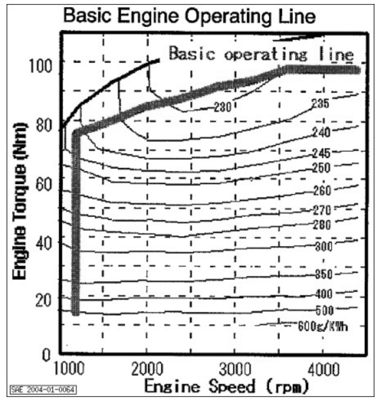

Fig. 6: ICE torque-speed lookup table

F. Planetary Gear

Planetary gear block of original MATLAB HEV model is mechanical and a little confusing so based on [14] we have designed a new and simple model which satisfies both torque and speed requirements (Fig. 7). There is another model for torque connection between generator, traction motor and vehicle differential which is not depicted here.

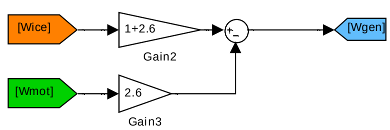

Fig. 7: Speed coupling model for planetary gear

G. Vehicle Dynamics

Since in DOE report there is no information on vehicle conditions, the parameters used in this model are based on both Toyota company reports and MATLAB default HEV model. Table II contains some of the parameters used as vehicle dynamics.

H. Vehicle Model Evaluation Results

Evaluation data has been elicited from DOE report. Since in DOE reports road condition has not been presented, through a procedure, it has been estimated. The road condition should be extracted for every drive test. After finding road condition, simulation has been done with the same drive cycle and road condition (Fig. 8 and 9). Fig (8-a) indicates drive cycle used for this simulation.

TABLE II
VEHICLE DYNAMICS

Description	Value
Mass(kg)	1360
Frontal Area(m^2)	2.57
Drag coefficient	0.26
CG height from ground (m)	0.5

The positive amount is considered as acceleration signal and negative amount is considered as brake signal. In Fig (8-(8-b) the output result of DOE report, as vehicle's speed, is compared with this Simulink model result. The digitized one

one is extracted from DOE report and the smooth one is Simulink model output for the same drive cycle. The last figure figure in this series (Fig 8-c) indicated battery SOC. We added another drive cycle result to the paper, Fig. 9. This one consists of only an acceleration drive cycle and has no brake time.

a)

b)

c)

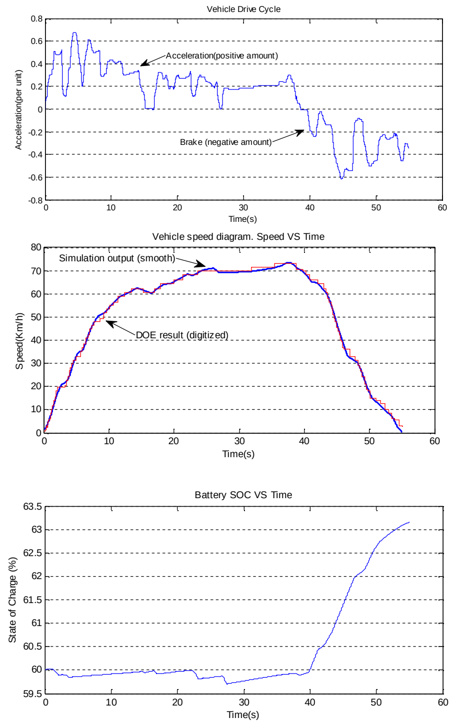

Fig. 8 First evaluation result output compared with DOE report (Fig A3 in DOE report). a) Drive cycle, b) vehicle speed and c) battery SOC

II. TRANSMOTOR

A. Static Model

Transmotor is an electric motor with a floating stator which forms a double-rotor machine with stator as outer rotor rotor and traditional rotor as inner rotor. Through the air gap, electric power converts into mechanical power as shown in in

Fig. 8. The stator electrical frequency in Transmotor is the relative speed of rotor (as inner rotor) to stator (as outer rotor). According to the action and reaction effects, in steady state rotor and stator torques are the same.

The speed relationship can be expressed as

$$\omega_e = \omega_r - \omega_s \qquad (1)$$

ωr and ωs are outer and inner rotor speeds respectively and ωe is the inner rotor (rotor) relative speed to the outer rotor (stator) and it is the electrical frequency of stator windings(Fig. 9). In steady state the torque relationships can be expressed as

$$T_{es} = T_{ms} = -T_{er} = -T_{mr} \qquad (2)$$

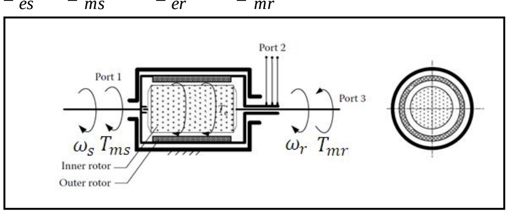

Fig. 9 Transmotor used as a speed coupler [1]

B. Dynamic Model

For simulation purposes, dynamic model of Transmotor have been used. The dynamic model of Transmotor is same as common synchronous PM machine but it has one extra mechanical equation for stator rotation. Equations (3)-(9) show this model.

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + p(\omega_r - \omega_s)\psi_{ds} \quad (3)$$

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - p(\omega_r - \omega_s)\psi_{qs} \quad (4)$$

$$\psi_{qs} = L_{qs} i_{qs} \quad (5)$$

$$\psi_{ds} = \psi_m + L_{ds} i_{ds} \quad (6)$$

$$T_{es} = -T_{er} = \frac{3}{2} p(i_{qs}\psi_m + (L_{ds} - L_{qs}) i_{ds} i_{qs}) \quad (7)$$

$$T_{es} = T_{ms} + J_s \frac{d\omega_s}{dt} + B_s \omega_s \quad (8)$$

$$T_{er} = T_{mr} + J_r \frac{d\omega_r}{dt} + B_r \omega_r \quad (9)$$

III. TOPOLOGY OF TRANSMOTOR BASED HEV

The topology we have used in this paper is shown in Fig. 10. The Engine power through Transmotor transfers to wheels and combined with traction motor, provides the moving force. The Transmotor acts as a speed coupler and the gears which connect it to differential, act as a torque coupler. The whole system acts as a torque-speed coupler which decouples simultaneous speed and torque of engine from required speed and torque on wheels. Therefore this topology results in a series-parallel vehicle [14].

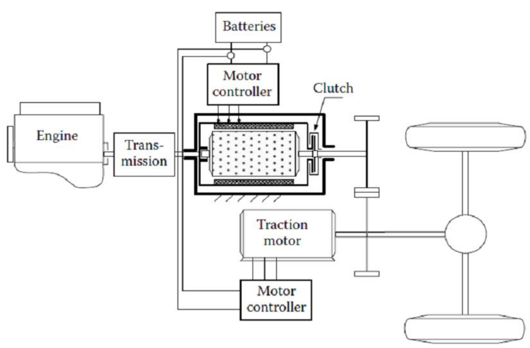

Fig. 10 New topology of series-parallel HEVs with Transmotor

IV. OPERATING MODES

This vehicle operates in several modes which, through a start - stop drive cycle, will be described. In starting and low speeds, only traction motor provides propelling torque. In this mode the engine is off and Transmotor provides no electric energy. When vehicle reaches a specific speed (24 km/h), or when the battery’s state of charge (SOC) comes down to a specific amount (40 percent), the engine starts and Transmotor acts as a speed coupler. It transfers engine power to differential. In this mode whenever the SOC of battery gets lowered the Transmotor recharges it.

In braking mode, traction motor acts as a generator and recharges the battery. If braking needs more negative torque and the traction motor could not provide it, a mechanical brake will provide the rest and act as an emergency brake.

V. COMPARING THE TWO POWER DIVIDERS

Data of an experimental test has been selected for comparing these two power dividers. The test contains acceleration, almost cruse time and deceleration or brake.

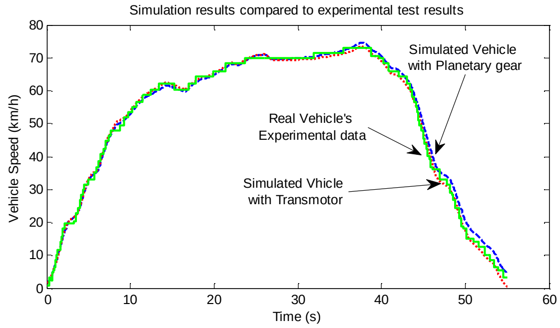

Fig. 11 Vehicles speed results. Real vehicle's experimental test data, simulated vehicle with planetary gear and simulated vehicle with Transmotor

In Fig. 11 three diagrams have been depicted for a) real vehicle experimental data b) simulated vehicle model test results with planetary gear and c) simulated vehicle test results with Transmotor.

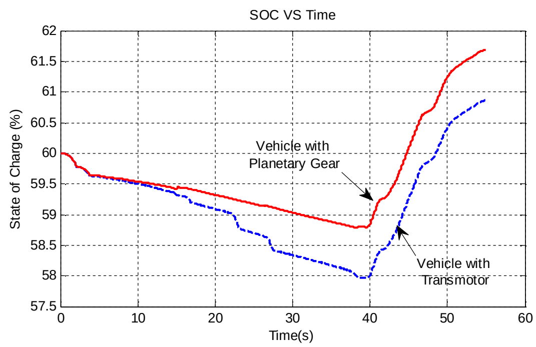

Fig. 12 Battery SOC compare: vehicle with planetary gear: continuous line; vehicle with Transmotor: dotted line

Fig. 12 reveals some facts about using the HEV with Transmotor. As it can be seen, in a vehicle with Transmotor as a power divider, battery SOC's range of changes is wider than when planetary gear is used. So a bigger battery is more appropriate for this vehicle. The bigger the battery get, the range of changes in SOC get narrower.

VI. SUGGESTIONS

In Transmotor power divider, since Transmotor transmits power from ICE to vehicle differential, a bigger battery pack will be needed. With a bigger battery pack, both vehicles provide the same demands and beside that the vehicle with Transmotor as a power divider, has a bigger capacity and could save more regenerative energy.

VII. CONCLUSION

In this paper a dynamic model for hybrid electric vehicle has been presented and evaluated with real experimental test data. The real model for this simulation is Toyota Prius 2004. After evaluating the model, its mechanical power divider has been replaced with an electromagnetic one and the new vehicle has been modified to have the same operating modes. Both of these vehicles have been tested under real experiment data and the results have been depicted. The results depict validity of both models according to real tests data elicited from U.S DOE reports. One important result for this comparison is that in Transmotor case a bigger battery pack should be used.

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